Rare B & D decays: a theoretical overview

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- Introduction
- Recent developments in quark-flavour mixing
- Selcted rare B decays
- A very brief look to D decays
- Conclusions

Introduction

To a large extent, the origin of "flavour" is still a mystery...
Our "ignorance" can be summarized by the following two open questions:

- *What determines the observed pattern of masses and mixing angles of quarks and leptons?*

- *Which are the sources of flavour symmetry breaking accessible at low energies?*
  [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

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Some “popular” answers to this question are obtained by means of

- Abelian or non-Abelian continuos flavour symmetries
- Discrete flavour symmetries
- Fermion profiles in extra dimensions

But other options are also possible.

In all cases it is quite easy to reproduce the observed mass matrices in terms of a reduced number of free parameters, while it is difficult to avoid problems with FCNCs (rare decays) without some amount of fine-tuning.

Hard to make progress without knowing the ultraviolet completion of the SM.

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- *Which are the sources of flavour symmetry breaking accessible at low energies?* [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

Answering this question is more easy:

- It can be formulated independently of the UV completion of the theory
- It is mainly a question of precision (both on the theory and on the experimental side): key role of rare decays

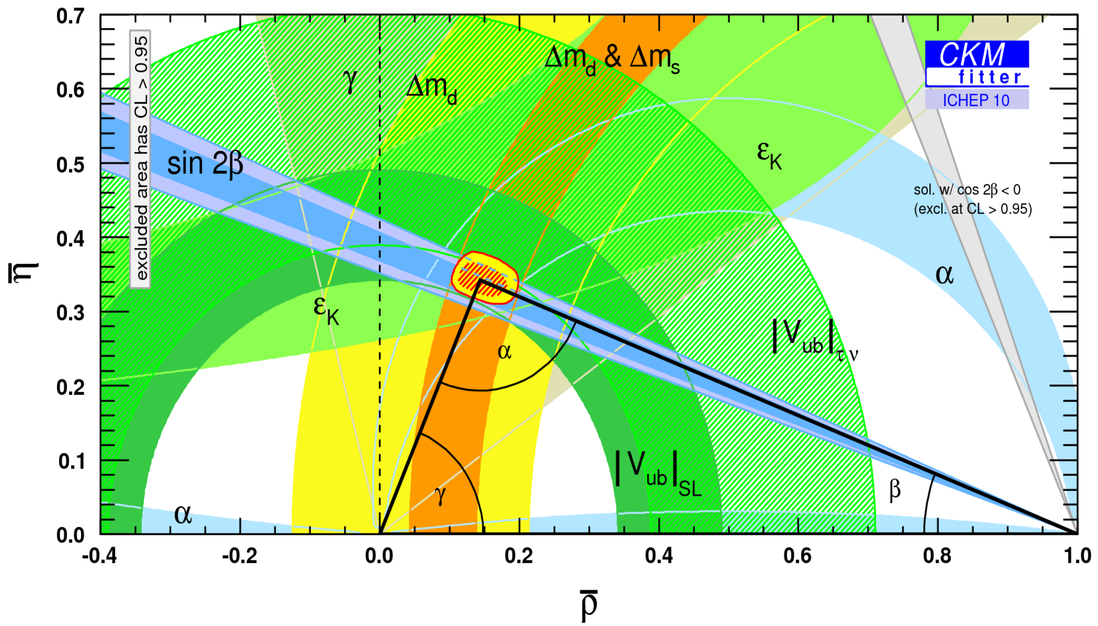
↓

Main goal of flavour-physics in the early LHC era

Recent developments in quark-flavour mixing

- Good overall consistency of the CKM picture

The leading contribution to flavour-changing processes is due to SM



New flavor-breaking sources of O(1) at the TeV scale are definitely excluded

Recent developments in quark-flavour mixing

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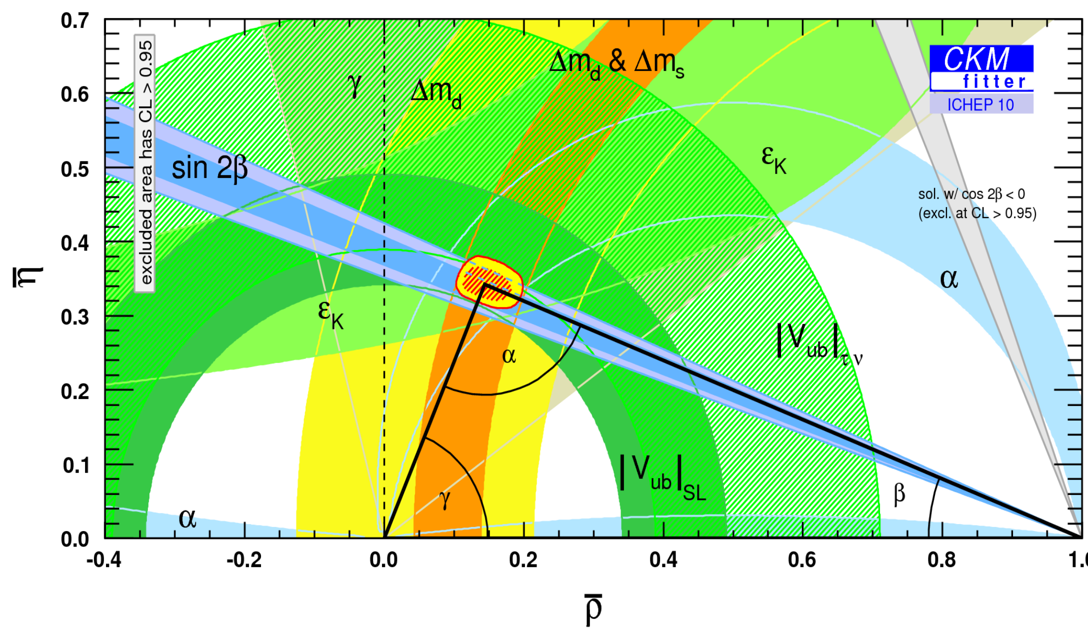


- But some "creeks" are emerging in some suppressed observables. Most notable examples:

  - The $A_{\psi K}$ - sin(2β) tension
  - CPV in Bs mixing
  - B→ τ ν

	SM pred.	data	pull
$A_{\psi K}$	.771 ± .036	.654 ± .026	2.7σ
$\phi_s = -2\lvert\beta_s\rvert$	.038 ± .003	~0.7 ± 0.3	~ 2σ
10^4 B(B→τν)	0.81 ± 0.07	1.72 ± 0.28	3.2σ

Recent developments in quark-flavour mixing

These deviations from the SM are quite "natural" (suppressed observables) and, at least in some cases, could be the first *signals of new dynamics at the TeV scale*

Two main options:

- Minimal Flavour Violation hypothesis: the new dynamics does not introduce new sources of flavour symmetry breaking [*flavour degeneracy broken only by the SM Yukawa couplings*].

- Beyond MFV: the new dynamics does introduce new (presumably small) sources of flavour symmetry breaking.

Key tool to make progress in this field is to identify correlations among different observables (epsecially rare decays) $\Rightarrow$ flavour pattern of the new dynamics at the TeV scale

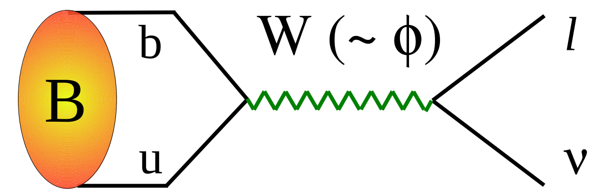
Selected rare B decays

A selected list of particularly interesting modes/observables:

- $B \to \tau\nu \ \ (l\,\nu)$
- $B \to l^+ l^-$
- $B \to K^{(*)} l^+ l^-$
- $B \to D\,\tau\nu$
- $B \to K^{(*)} \nu\nu$

$B\to \tau \nu$

The helicity suppression of the SM amplitude makes $B\to\tau\nu$ an excellent probe of models with an extended Higgs sector



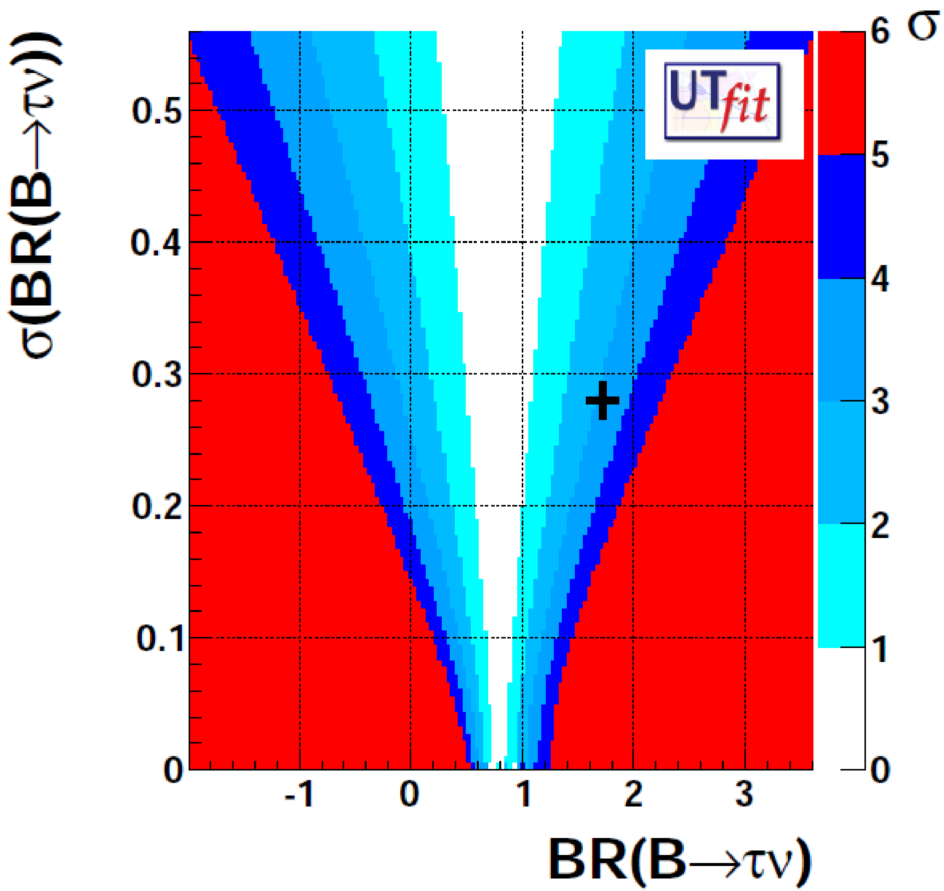
longitudinal comp. of the W

$$B(B\to l\nu)_{SM} = C_0\, f_B^{\,2}\, |V_{ub}|^2$$

Very clean test of the SM, <u>provided</u> reliable independent infos on f_B & V_{ub}

$$B(B\to\tau\nu)_{exp} = (1.68 \pm 0.31)\times 10^{-4}$$

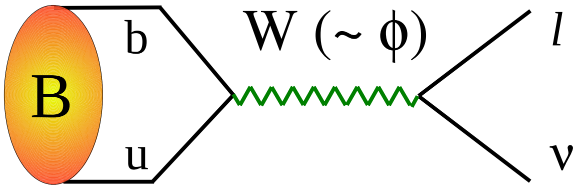
$B_{SM} = (0.79 \pm 0.07)\times 10^{-4}$ UTfit '10 [global fit]



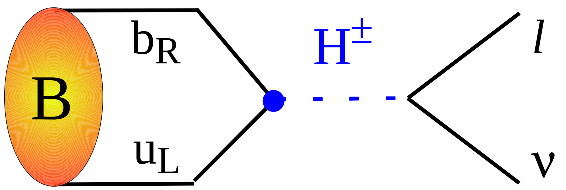
$B \to \tau\nu$

The helicity suppression of the SM amplitude makes $B \to \tau\nu$ an excellent probe of models with an extended Higgs sector, such as the MSSM...

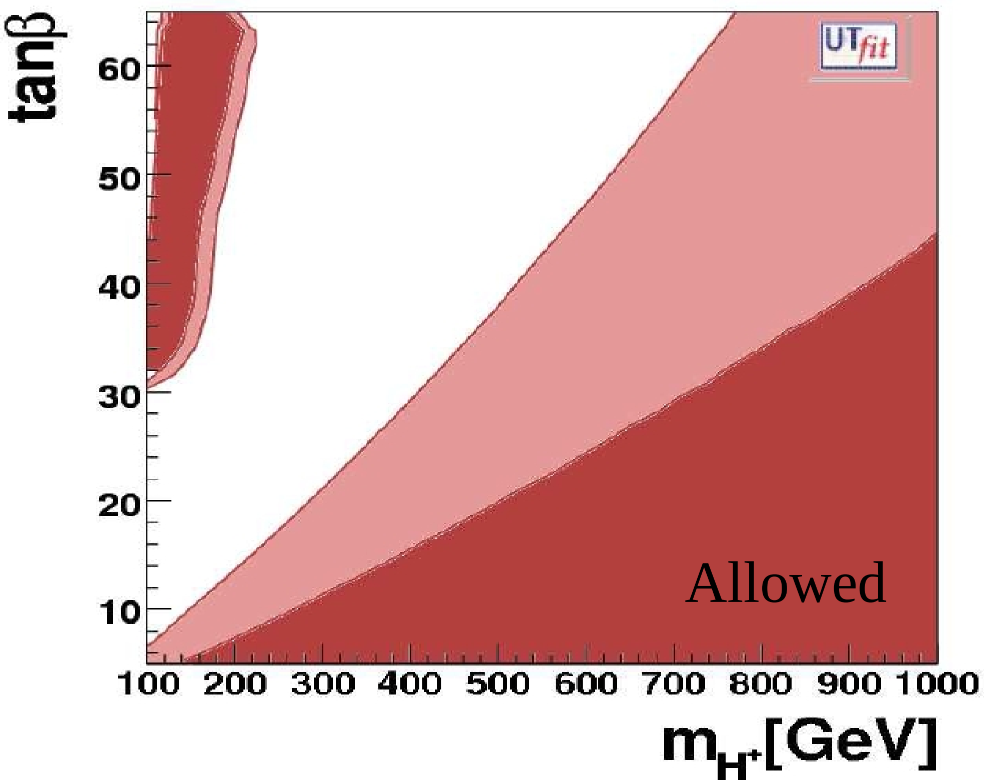
$$\mathcal{B}(B \to l\nu) = \mathcal{B}_{SM}\left(1 - \frac{m_B^2 \tan\beta^2}{M_H^2 (1+\epsilon_0 \tan\beta)}\right)$$



longitudinal comp. of the W



extra tree-level contribution
simple M_H & $\tan\beta$ dependence



Very significant constraint on 2HDM & MSSM at large $\tan\beta = v_2/v_1$, with great potential of improvement in the future

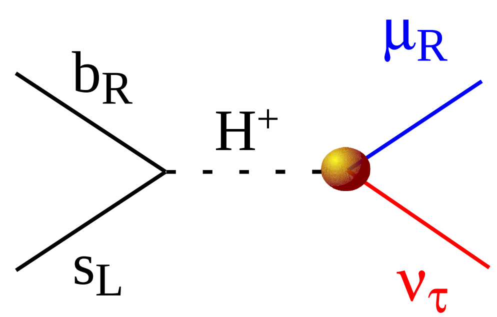
N.B.: *in the simplest version of these models the effect is negative...*

$B \to l\,\nu$

More exotic possibilities on $B \to l\nu$: if the model has sizable non-minimal sources of flavour symmetry breaking in the lepton sector $\Rightarrow$ large violations of lepton-flavour universality

$$\Gamma(B \to \mu\nu)^{\rm exp} = \Gamma(B \to \mu\nu_\mu) + \Gamma(B \to \mu\nu_e) + \Gamma(B \to \mu\nu_\tau)$$

$\approx$ SM $\qquad \approx 0 \qquad$ scalar LFV amplitude



Possible probe of this effect in the ratios:

$$R^B_{\mu\tau} = \frac{\Gamma(B^+ \to \mu^+\nu)}{\Gamma(B^+ \to \tau^+\nu)} \qquad R^B_{e\tau} = \frac{\Gamma(B^+ \to e^+\nu)}{\Gamma(B^+ \to \tau^+\nu)}$$

$$\Delta \sim 10\%\ (R^B_{\mu\tau})^{SM} \qquad \sim 10^3 \times (R^B_{e\tau})^{SM}$$

G.I. & Paradisi '06
G.I. & Filipuzzi '09

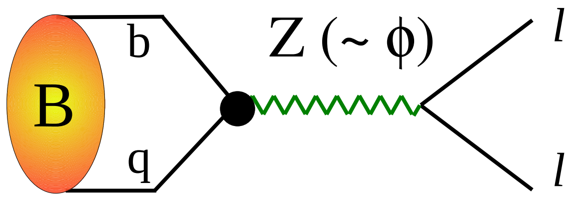
Interesting correlation with the same phenomenon in the Kaon system, which so far set the best upper limit

$$R^K_{\mu e} = \frac{\Gamma(K^+ \to \mu^+\nu)}{\Gamma(K^+ \to e^+\nu)} \longrightarrow \Delta \sim 1\%$$

$B_{s,d} \to l^+ l^-$

These rare decays are both <u>helicity suppressed</u> and <u>GIM suppressed</u> (FCNC)

Excellent probes of models with 2 Higgs doublets (such as the MSSM) at large/moderate tanβ



longitudinal comp. of the Z (one-loop indiced Z penguin) + realted box amplitude

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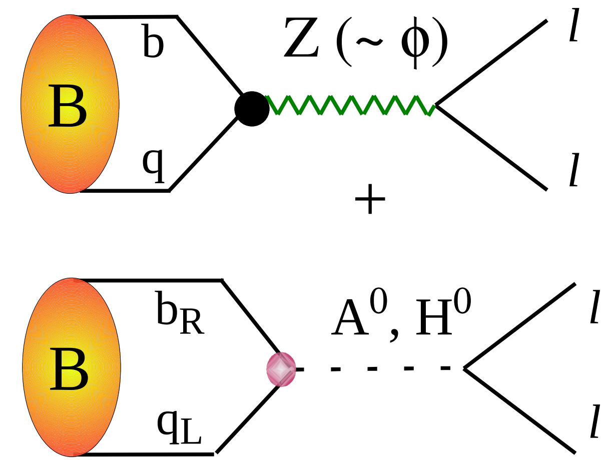

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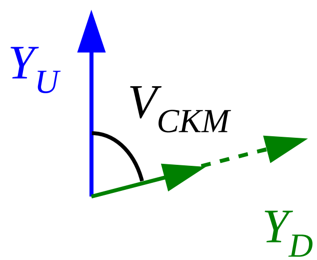
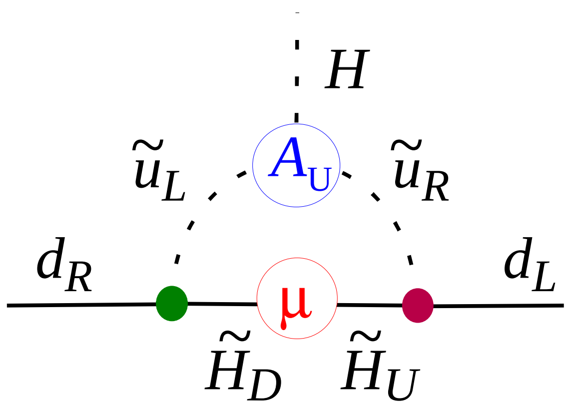


$$\mathrm{diag}(Y_U) = \mathrm{diag}(m_u) \,/\langle H_U\rangle$$

$$\mathrm{diag}(Y_D) = \mathrm{diag}(m_d) \,/\langle H_D\rangle \;=\; \tan\beta \; m_d \,/\langle H_U\rangle$$

Even in MFV, the different normalization of the Yukawa couplings induces an effective <u>Higgs-mediated FCNC coupling</u>:

No impact in helicity-conserving processes, but possible large effect in $B \to l^+ l^-$



Nice link with models explaining ΔF=2 anomalies

$B_{s,d} \to l^+ l^-$

Present exp. status:

$B(B_s \to \mu\mu) < 4.8 \times 10^{-8}$ (95%CL)

$B(B_d \to \mu\mu) < 7.6 \times 10^{-9}$ (95%CL)

[CDF '09]

SM expectations:

$B(B_s \to \mu\mu)_{SM} = 3.2(2) \times 10^{-9}$

$B(B_d \to \mu\mu)_{SM} = 1.0(1) \times 10^{-10}$

e channels suppressed by $(m_e/m_\mu)^2$

τ channles enhanced by $(m_\tau/m_\mu)^2$

Within the MSSM, wit MFV:

$$A(B \to ll)_H \sim \frac{m_b m_l}{M_A^2} \frac{\mu A_U}{\tilde{M}_q^2} \tan^3\beta$$

Possible large enhancement over the SM but the magnitude of the effect can vary a lot in different SUSY-breaking scenarios

- Th. error controlled by f_B ($\Rightarrow$lattice). Not a big issue if deviations from SM are large, but important to improve in view of future precise measurements
- The $B(B_d \to \mu\mu)/B(B_s \to \mu\mu)$ ratio is a key observable to proof or falsify MFV

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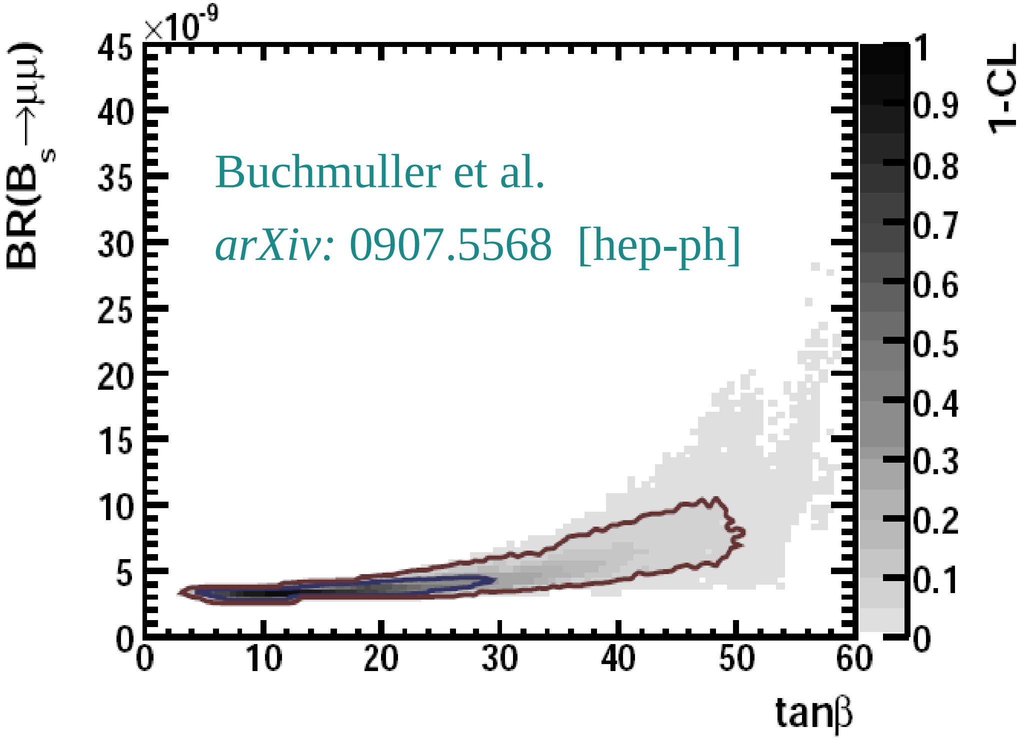
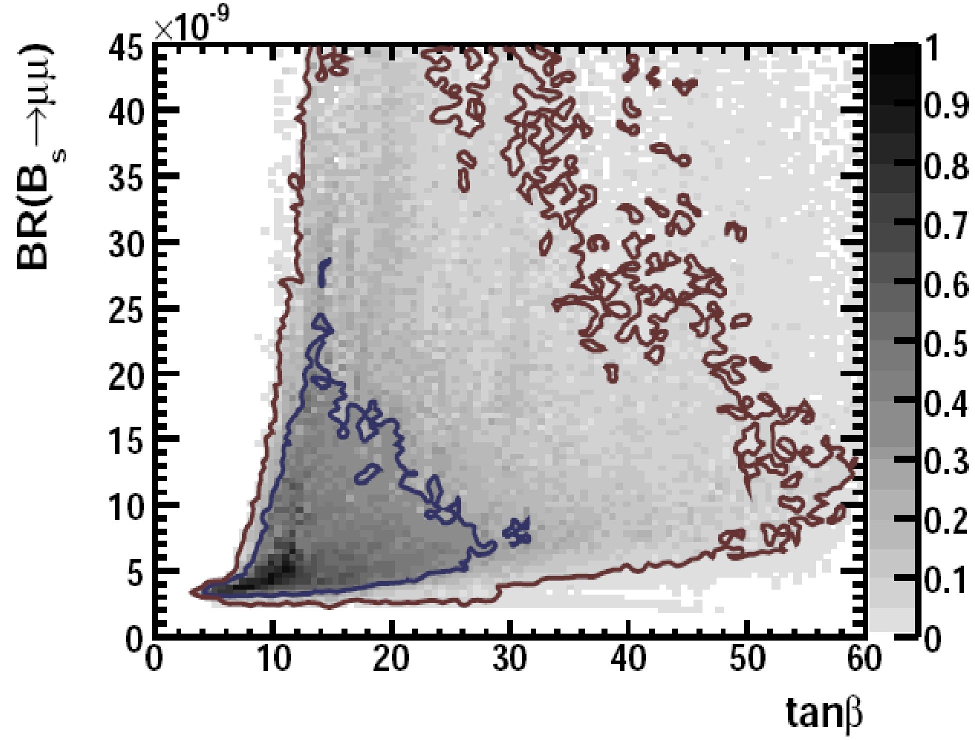
Constrained - MSSM



Constrained – MSSM with non-universal Higgs masses (NUHM)



Reaching the SM level would lead to a very significant constraint in the (C)MSSM

$B \to K^{(*)} l^+ l^-$

The accuracy on these FCNC decays depends on the th. control of $B \to K, K^*$ *hadronic form factors* :

$$A(B \to f) = \sum_i C_i(\mu) \langle f | Q_i | B \rangle (\mu) \qquad \mu \sim m_b$$

⇒ several progress in the last few years [SCET, LCSR, Lattice] but typical errors still ~ 30%

The most difficult observables are the total branching ratios, th. errors are considerably reduced in appropriate ratios or differential distributions.

Notable example: A_{FB} $(B \to K^* l^+ l^-)$

$$\overline{A}_{FB} = \frac{d\Gamma(\cos\theta>0)/ds - d\Gamma(\cos\theta<0)/ds}{d\Gamma(\cos\theta>0)/ds + d\Gamma(\cos\theta<0)/ds}$$

$B \to K^{(*)} l^+ l^-$

$$A_{FB} = \int \frac{d^2 B(B \to K^* \mu^+ \mu^-)}{d\cos\theta} sgn(\cos\theta) \;\propto\; \mathrm{Re}\{C_{10}^* [q^2 C_9^{eff}(q^2) + r(q^2) C_7]\}$$

θ = angle between μ^+ & B in the dilepton rest frame

q^2 = dilepton invariant mass

- C_7: γ penguin [dipole] ⇔ b→sγ
- C_9^{eff}: γ peng. [vector] + (Z & box)
- C_{10}: Z peng. + box [axial]

- Interference of axial & vector currents ⇒ direct access to the *relative phases* of the Wilson coefficients
- Uncertainties of hadronic form factors under control in the low-q^2 region (pQCD, sum-rules)

Beneke, Feldmann, Seidel '01

⬇

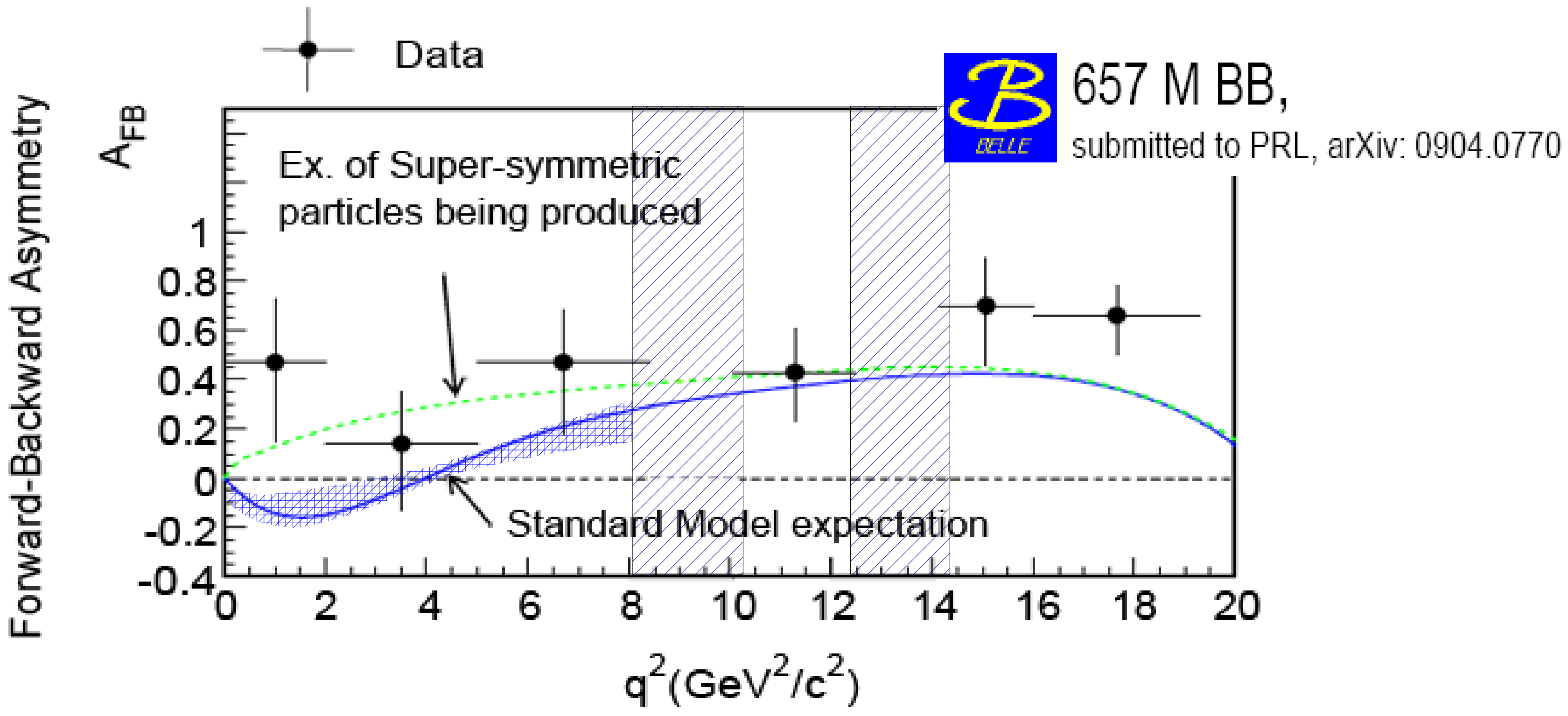
Sensitive test of various realistic extensions of the SM (e.g. non-standard Zbs effective coupling)

Ali *et al*. '00; Buchalla *et al*. '01

[...] Altmannshofer *et al*. '09

$B \to K^{(*)} l^+ l^-$

Belle has recently reached an interesting sensitivity on this observable:



The agreement with SM expectations is not perfect (but claiming a significant deviation is definitely premature!) LHCb/Tevatron will find out if the discrepancy is serious...

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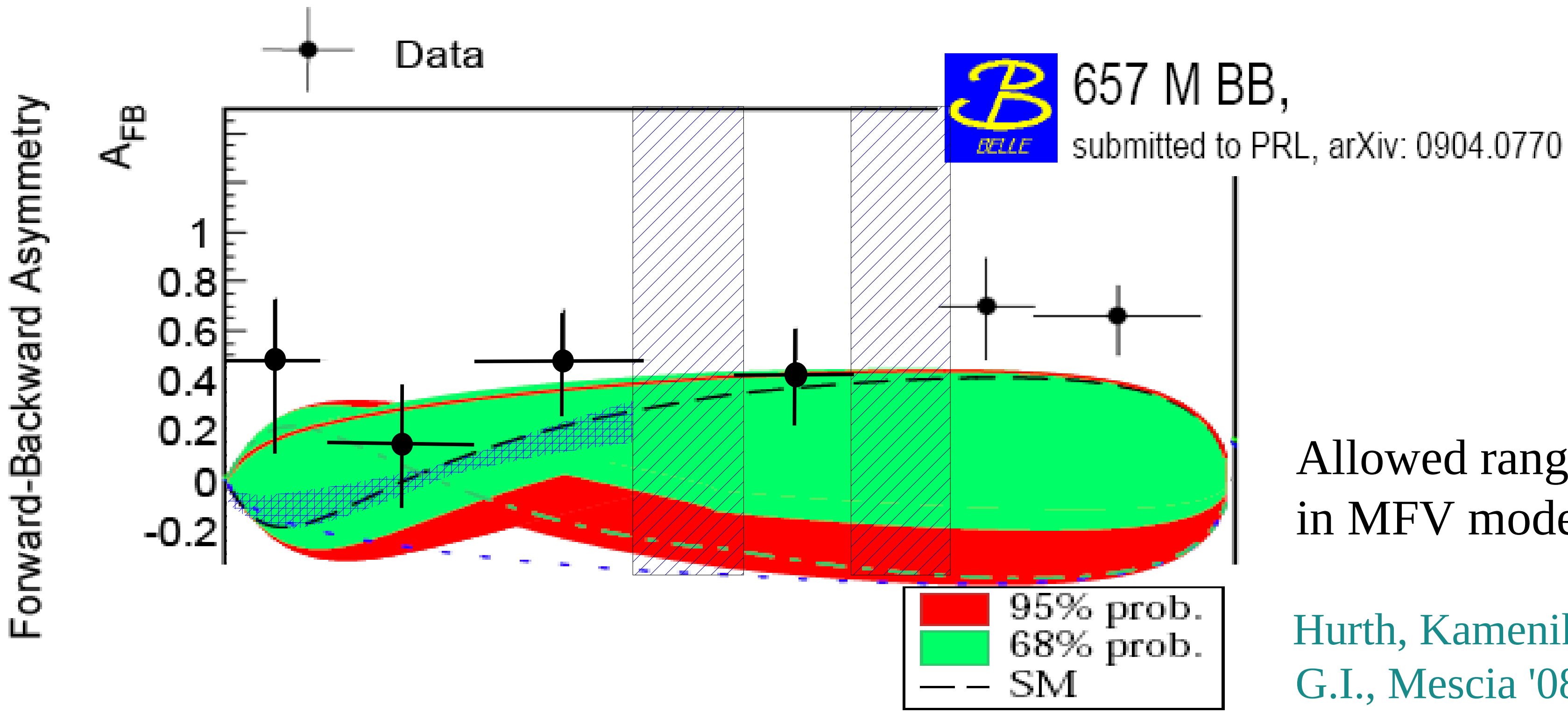

Allowed range in MFV models

Hurth, Kamenik
G.I., Mescia '08

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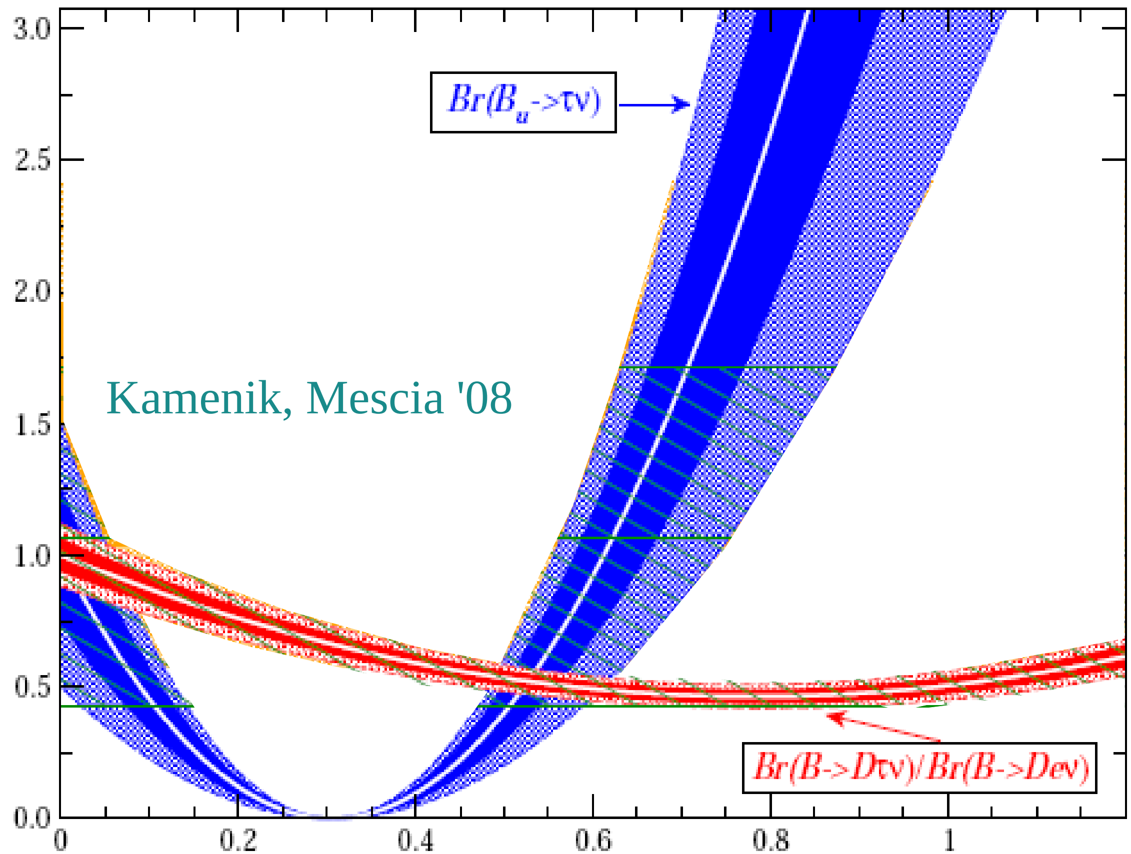
Certainly large room for NP even in “conservative” beyond-SM models

$B \to D\tau\nu$

NP sensitivity similar to $B \to \tau\nu$ (*interesting for hadron mchines ?*): good sensitivity to charged-current scalar amplitudes (large τ Yukawa coupling) [typical size of deviation from SM: ~30-40% smaller than in $B \to \tau\nu$]

Theory uncertainty (hadronic form factors) substantially reduced (below 10%) if the rate is normalised to $B \to De\nu$ [possible further improvement with Lattice QCD]

$$\left.\frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to De\nu)}\right|_{SM} = (0.28 \pm 0.02)$$



$$\frac{m_b m_\tau \tan^2\beta}{M_H^2 (1 + \epsilon_0 \tan\beta)}$$

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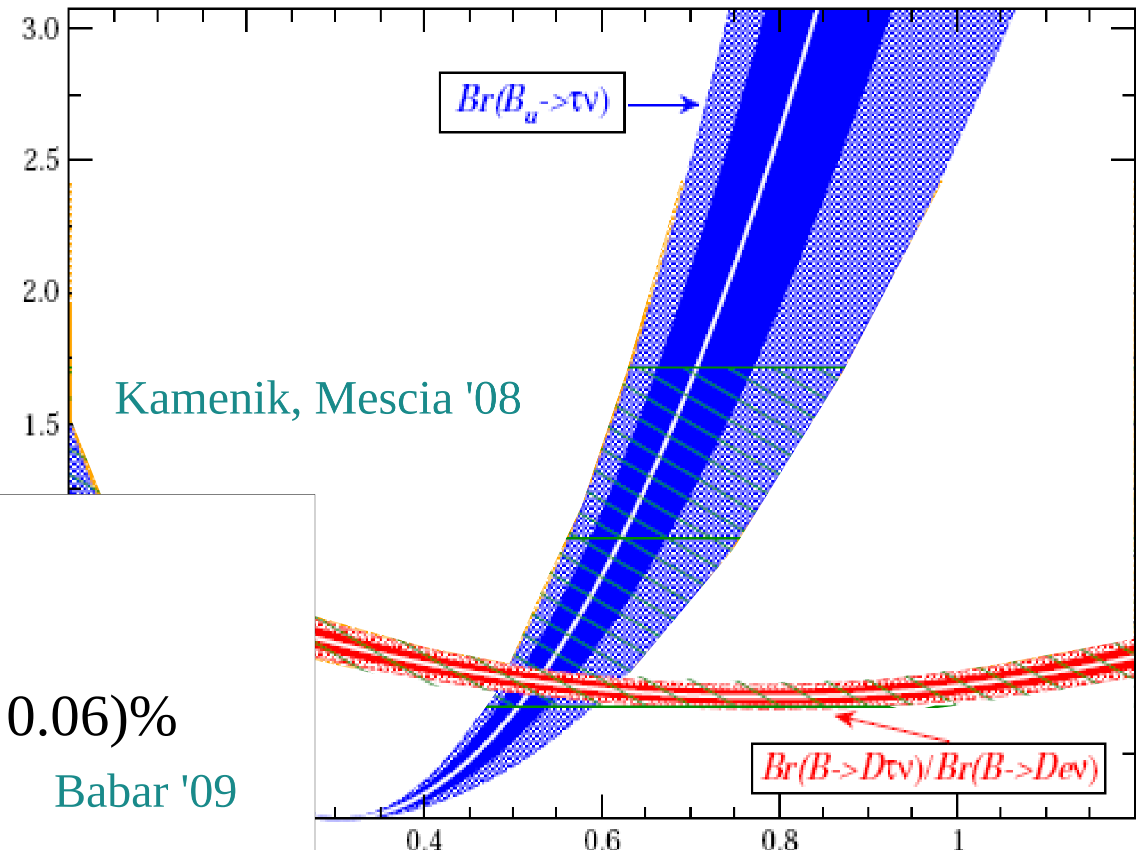


$$\frac{m_b m_\tau \tan^2\beta}{M_H^2 (1+\epsilon_0 \tan\beta)}$$

$$B(B \to D\tau^+\nu)_{SM} \approx 0.65\ \%$$

$$B(B \to D\tau^+\nu) = (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\%$$

Babar '09

$$B(B^+ \to D^0\tau^+\nu) = (1.51\ ^{+0.41}_{-0.39}\ ^{+0.24}_{-0.19} \pm 0.15)\%$$

Belle '09

$B \to K^{(*)} \nu\nu$

Extremely "clean modes" both within and beyond the SM (virtually no long-distance contributions):

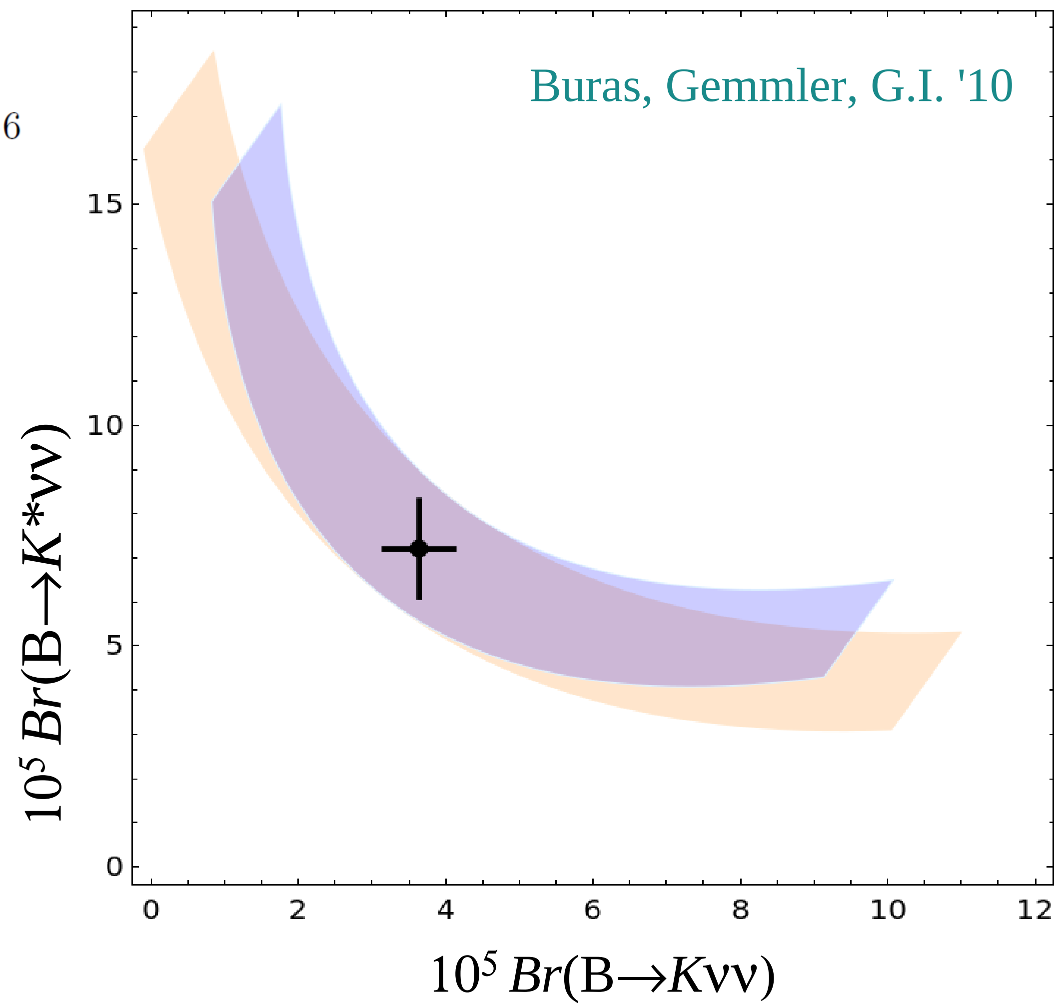
$$\mathcal{B}(B \to K \nu\bar{\nu})_{\rm SM} = (3.64 \pm 0.47) \times 10^{-6}$$
$$\mathcal{B}(B \to K^* \nu\bar{\nu})_{\rm SM} = (7.2 \pm 1.1) \times 10^{-6}$$

Kamenik, Smith. '09
Bartsch *et al*. '09

$$\mathcal{B}(B \to K \nu\bar{\nu}) < 1.4 \times 10^{-5}$$
$$\mathcal{B}(B \to K^* \nu\bar{\nu}) < 8.0 \times 10^{-5}$$

Babar & Belle '08-'09

E.g.: $B \to K\nu\nu$ vs. $B \to K^*\nu\nu$ with RH currents (interesting model to explain the "Vub puzzle")



A very brief look to D decays

In most realistic NP rare *D* decays are not too interesting for NP searches [*large LD contrib. which is difficult to suppress* - most interesting oservable in the *D* system is *CPV in D mixing*]

But we should be open also to more exotic possibilities. In this respect rare D decays offer some interesting SM null-tests:

- $D \to \mu^+\mu^-$ $BR_{SM} \sim few\ 10^{-13}$
- $D \to \mu\, e$ $BR_{SM} \sim 0$
- ...

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Model	$\mathcal{B}_{D^0\to\mu^+\mu^-}$
Experiment	$\leq 1.3 \times 10^{-6}$
Standard Model (SD)	$\sim 10^{-18}$
Standard Model (LD)	$\sim$ several $\times 10^{-13}$
$Q = +2/3$ Vectorlike Singlet	4.3×10^{-11}
$Q = -1/3$ Vectorlike Singlet	$1 \times 10^{-11}\ (m_S/500\ \mathrm{GeV})^2$
$Q = -1/3$ Fourth Family	$1 \times 10^{-11}\ (m_S/500\ \mathrm{GeV})^2$
Z' Standard Model (LD)	$2.4 \times 10^{-12}/(M_{Z'}(\mathrm{TeV}))^2$
Family Symmetry	0.7×10^{-18} (Case A)
RPV-SUSY	$4.8 \times 10^{-9}\ (300\ \mathrm{GeV}/m_{\tilde{d}_k})^2$

Golowich et al. '09

Conclusions

To a large extent, the origin of "flavour" is still a mystery...

But we are making progress:

- We have understood that large new sources of flavour symmetry breaking at the TeV scale are excluded
- But several anomalies in the CKM picture are starting to show up: some of them will go away, some others (with some optimism...) may well be the *first signals of new physics at the TeV scale*.
- Rare decays are the key tool to make progress in this field:

  They allow us to identify correlations among different non-standard effects $\Rightarrow$ flavour pattern of the new symmetry breaking terms.

  Clean leptonic/semileptonic *B* decays are those with the largest discovery power in most realistic NP models